Запропоновано метод формалізованого предикативного визначення зон безпечної та небезпечної областей навігації при впливі на рухоме судно зовнішніх факторів. Доведено умови, що під час конфліктної ситуації забезпечують гарантоване визначення безпечної траєкторії руху судна від початку маневра до повернення на плановий маршрут. Запропонований спосіб параметричного опису обмежень на пограничні умови запобігання входу у небезпечні області навігації реалізує рух по трансверсальним безпечним траєкторіям

Ключові слова: ефективна безпека, умови запобігання зіткнень, система адаптивного руху, динаміка позиціонування

Предложен метод формализованного предикативного упорядочения зон безопасной и опасной областей навигации при воздействии на движущееся судно внешних факторов. Доказаны условия, которые обеспечивают гарантированное упорядочение безопасной траектории движения судна от начала маневра до возвращения на плановый маршрут. Предложенный способ параметрического описания ограничений на пограничные условия предотвращения входа в опасные области навигации позволяет движение по трансверсальным безопасным траекториям

Ключевые слова: эффективная безопасность, условия предотвращения столкновений, система адаптивного движения, динамика позиционирования

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ANALYSIS AND ALGEBRAIC-SYMBOLIC DETERMINATION OF CONDITIONS FOR SAFE MOTION OF A VESSEL IN A NON-STATIONARY ENVIRONMENT

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1. Introduction

Mathematical methods and computer technologies applied in combination ensure practical significance of results of solving important tasks in navigation. A timely decision enables the possibility to fulfill on time a proper control law within a complex dynamic system (CDS). Proof of this is given in research papers [1–6]. The current conditions of navigation do change and almost accidentally turn into threatening forms of influence exerted by the external adverse environment (EAE) on water transport (wind, waves, currents, tides, fog, sudden changes in weather conditions, approaching a potentially dangerous object or other vessels, failure of technical means, etc.). Depending on the actual circumstances, there may occur different possible consequences of rational response from all hierarchical subsystems of CDS.

First, when the degree of danger is within tolerance ε, then the law of control $U(t, X, W)$, X is the vector of parameters of the state of controlled movable object, W is the vector of threats of factors EAE, corresponds to the stabilization modes of internal parameters of the vessel and kinematic monitoring relative to the planned motion route on the navigating water area [6, 7]. This is a normal long mode for a safe navigation area (SNA) at operation with EAE noises [8–13].

Second, when a vessel deviates from the planned trajectory as a result of permissible pulse perturbations (in terms defined by $f(\varepsilon, \delta)$ constraints), then the problems of guaranteed adaptive control (GAC) are resolved. This makes it possible to compensate for the undesired effects of EAE by utilizing energy resources available aboard. After these influences are compensated, transitional or maneuverable mode ends and the vessel continues to move according to the planned motion trajectory, which is the target for a given voyage [14].

Third, there may occur situations when a geometrical distance between the vessel and a potentially dangerous object no longer makes it possible to prevent the contact, as required by International Regulations for Preventing Collisions at Sea, dated 1972 [15]. In this case, when approaching the state of inevitable crash, there remain only automated modes for enabling the urgent means of life-saving in a dangerous navigation area (DNA). There is a known example of entering a DNA when the superliner *Costa Concordia* ran aground on January, 2012 on the Italian coast near the island of Giglio resulting in the hole with a length of 70 m, the loss of the vessel and tens of passengers. Material damage as a result of this accident amounted to about EUR 2 billion [16].

High Risk Areas (HRA) in sea waters exist in many geographical areas. Traffic Separation Schemes are implemented in accordance with the IMO Resolution A.572 (14) dated November 20, 1985 [17, 18]. The requirements of international conventions, including the International Regulations for Preventing Collisions at Sea, 1972, as well as significant efforts of international and domestic scholars, are focused on finding optimal methods to control motion modes of the vessel under non-stationary conditions. However, despite the above, the situation with accidents in maritime transport does not change significantly. The level of failures in the global maritime fleet remains unsatisfactory. This confirms the relevance of present research.

2. Literature review and problem statement

International statistics about emergency events on transport, specifically maritime transport over the period of 2010–2015, testifies to the significant level of accident rate, despite considerable advances in technology and many years of work by scientists in the direction of safety. The losses of international sea fleet, for the type and cause of destruction of vessels [19, 20], are given in Table 1, 2 and in Fig. 1, 2. As statistical data, provided by these sources, reveal, the largest number of vessels that were lost in the sea were the unspecialized dry cargo vessels, with the most frequent causes of loss being the loss of buoyancy and running aground. In other words, it happened when a vessel directly entered a dangerous navigation area (DNA) and while a vessel was exposed to the critical EAE impact.

Table 1

Losses of vessels in world trade fleet over 2010–2015 for the types of vessels

Vessel types	2010	2011	2012	2013	2014	2015	Total
Dry cargo	60	37	61	41	31	36	266
Bulkers	11	14	9	15	4	6	59
Passenger	3	7	7	8	10	4	39
Tugs	7	2	6	7	7	7	36
Chemical tankers	5	2	8	10	2	2	29
Ro-Ro	1	3	4	2	5	4	19
Container vessel	5	3	6	4	4	5	27
Other types	3	5	3	6	4	2	23
Suppliers	2	2	3	2	3	2	14
Barges	1	0	0	3	1		5
Dredgers	2	2	2	0	1	1	8
Oil tankers	3	3	1	0	1	0	8
Gas tankers	1	1	1	0	0	0	3
Grand total	104	81	111	98	73	69	536

Table 2

Causes of losses of vessels in world trade fleet over 2010–2015

Causes of Losses	2010	2011	2012	2013	2014	2015	Total
Submerged	64	45	55	70	50	63	347
Wrecked/ stranded (aground)	23	28	26	21	18	12	128
Fire/explosion	11	8	13	15	6	3	56
Machinery damage	4	6	15	2	5	2	34
Collision	10	3	5	2	2	3	25
Hull damage	4	3	6	1	4	2	20
Miscellaneous	6	1	1	1	2	0	11
Hall contact	0	0	2	0	1	0	3
Piracy	2	1	0	0	0	0	3
Missing	1	0	0	0	0	0	1
Grand total	125	95	123	112	88	85	628

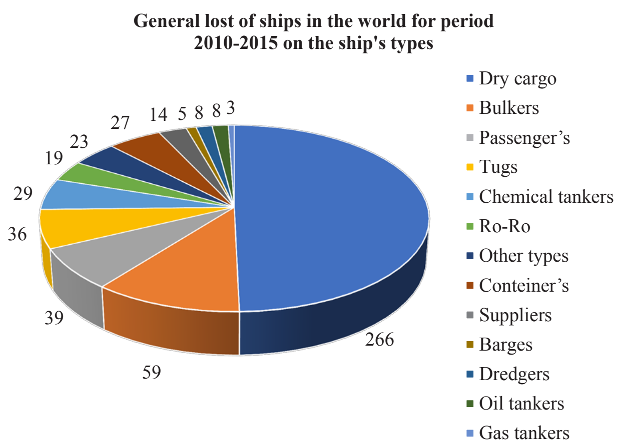

Fig. 1. Losses of vessels in world trade fleet over 2010–2015 for the types of vessels

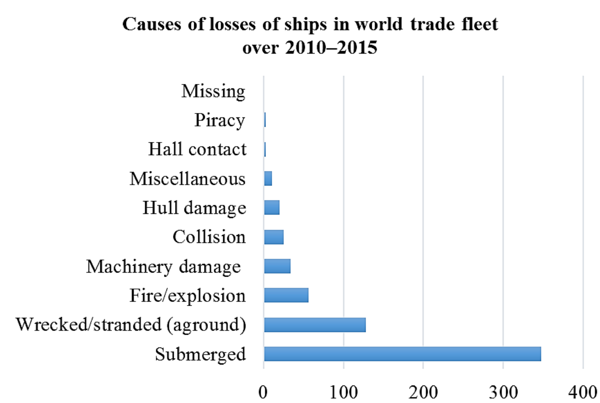

Fig. 2. Causes of losses of vessels in world trade fleet over 2010–2015

The quality of GAC over vessel motion for the criteria of invariance to a whole class of perturbations is achieved by applying intelligent technologies. It is advisable to substantially change the form of interaction between ergatic complexes, saturated by the means of automation based on computer technology [6, 8].

According to [6], the theory of vessel maneuvering was designed for the motion of a vessel in calm water. But the moving vessel is constantly affected by variable factors of irregular waves that need to be taken into account for calculating a timely safe maneuver.

According to [8], the result of wave interference is the emergence of a complex system of hills and valleys. The vessel experiences irregular pitching with some waves reaching giant size and appearing from the most unlikely direction. If the vessel happens to be on the crest of such a wave by a lag to the wind, there is a high probability of loss of stability and vessel capsizing. To prevent such accidents, there should be a detailed current information about all components of interference of a wave system interference (mean length, phase velocity relative to the vessel, etc.), as well as a forecast of the possible emergence of especially large waves along the course of the vessel.

In addition, according to [1], a Nomoto Gain analysis and the vessel maneuvering parameters Norbin allow control system to perform timely maneuvers only to low-speed vessels.

According to [2], practical use of the robotized surface and underwater vehicles significantly depends on weather conditions, first of all, on the size and irregularity of waves. The issue about vessel motion in a heterogeneous wave environment was also not tackled.

According to [4], despite promising innovative work on the development of new types of autopilots for vessels, the industry, due to economic reasons, does not implement more complex and expensive designs of controllers for the autopilots. Thus, it is an important issue to develop more reliable and relatively cheap algorithms to process commands in order to compensate for the influence of external factors.

In accordance with [9], the research undertaken over last decades has addressed integrated methods that would work well in two dimensions. In this case, there were difficulties in extending the accuracy of research results to three dimensions, especially under conditions of turbulence.

According to [21], adaptive feedback controller in the control units of input data on a moving object has only one parameter to update information. In this case, given only one parameter, the controller is limited in its capability to make a decision about unknown subsystem functions for all constraints.

Modern intelligent integrated technologies of navigation operate based on the principles of sampling and algebraization of sets of variable arguments, for example, the invariance of GAC over the motion of the particular i-th vessel. They significantly alter the functions of interaction between computer machines and intelligent agents of the system (IAS) at a polyergatic technological organization (PETO) [22].

Guaranteed active traffic safety of a vessel in HRA at threatening factors DNA_j implements three categories of navigation protection without collisions and disasters.

The first category of PETO ensures strategic effectiveness of transportation operations through planning, optimization, ensuring the profitability of a route, taking into account each HRA, reliability of stormy weather, the specificity of influence of particular factors of EAE. Reliable variants for early departure to safe waters are predicted.

The second category of PETO ensures tactical survivability, as well as completeness of resourcing for the implementation of maneuverable transitions from DNA to a safe navigation area (SNA). In this case, it is guaranteed that DNA is reliably enough identified relative to the boundary parameters in the space of actual threats of EAE. In this case, it is guaranteed that DNA is reliably enough identified relative to the boundary parameters in the space of actual threats of EAE. Under these conditions, it is necessary to minimize the cost of resources used for entering SNA*j*, which makes it possible, following a tactical maneuver, to return to SNA*i* to complete planned strategic transition to the destination port.

The third category of PETO does not yet guarantee the operational speed in the implementation of GAC laws over the motion of a vessel without accidents. In every particular water area, the realization of problems of the first two categories proceeds in parallel. Functional speed for variable SNA*ij* and DNA*j* under conditions of approximate closeness of zones i and j on the rectangular grid of zones i and j at $j \in J,\ \forall j \in N$ constructs on the rectangular grid $\forall(i,y) \in N$ the actual route of a given voyage under all non-stationary conditions of navigation.

Functional speed for variable SNA*ij* and DNA*j* under conditions of approximate closeness of zones i and j on the rectangular grid of zones i and j at $j \in J,\ \forall j \in N$ constructs on the rectangular grid $\forall(i,y) \in N$ the actual route of a given voyage under all non-stationary conditions of navigation.

Space-time continuum (STC) for each level of the guaranteed active safety of a vessel has a significant pattern and specificity of the models, based on which timely calculations are performed and the key problems of a given category are solved. In accordance with the International Convention for the Safety of Life at Sea (SOLAS) [23] and the resolution of the International Maritime Organization (IMO) MSC.282 (86), dated June 5, 2009, all categories of sea vessels are equipped, instead of paper maps, with the software–hardware complexes of type ECDIS (Electronic Chart Display and Information System) [24]. However, the process of planning the route of a voyage in accordance with the IMO resolution A.893(21) [7] is not automated up to now. The complexity of all technical, technological, and ergatic forms of interaction aimed at achieving the guaranteed level of safety for a vessel when approaching DNA where there is already an emergency threatening situation (ETS) requires innovative forms for navigation services under critical extreme conditions [5, 8].

The list and areas where a manifestation of ETS is possible are compiled for each actual HRA, bypassing which ensures navigation without accidents and disasters. Accurate and timely positioning of the geometry of STC for ETS and HRA on electronic maps using the modernized ECDIS makes it possible to adequately respond and adjust the basic K-th route $SNA_{K-1} \Rightarrow SNA_K \Rightarrow SNA_{K+1}$ to the transition areas SNA_{ij} of alternative maneuvering trajectories.

The role of strategic control is represented by a staged characterization of the K-the route to approaching with a bypass $DNA_{i+1} = (ETS \cup HRA)_{i+1}$ in the form

$$SNA_K \Rightarrow ....SNA_{i-2} \to SNA_{i-1} \to SNA_i \to$$
$$\to \left\{SNA_{ij} \to SNA_{K-p}\right\} \to SNA_{K-(p+1)} \to ... \Rightarrow SNA,$$

where ETS is the emergency threatening situation; the maneuver is performed in $\left\{SNA_{ij} \to SNA_{K-p}\right\}$ and the route continues along the planned trajectory until its safe arrival at the port of destination.

Instead of $DNA_{i+1} = (ETS \cup HRA)_{i+1}$, navigation follows an alternative-situational route $\left\{SNA_{ij} \to SNA_j\right\}$, which ensures the absence of intersections and entry to DNA in line with standard rules. It should be emphasized that SNR for all variants is realized at motion speed that satisfies the schedule of staged implementation of voyage $SNA_N \Rightarrow SNA_K$ along the programmed-optimal route [7].

Thus, for the case of implementation of a vessel voyage along the assigned planned route with DNA parameters satisfying the criteria of classification as the standard, motion of the vessel is executed in line with stages of SNR of a given plan. In all other cases, the situation is categorized as potentially dangerous "EXCEPTION: interrupt".

The essence of this type of classification of a special situation is the interruption of the previous planned SNA_i mode of navigation and transition to another operating mode SNA_{ij}, for example, by reason of "no good weather" [8, 25].

3. The aim and objectives of the study

The aim of present research is operational determining of transversal transitional trajectories of the vessel in HRA by updating the operation of parallel basic tools of information-control subsystems in a unified automated system for navigation and motion control of vessels. This should provide for the guaranteed safety of the vessel, complete cycle of transportation work, and environmental safety, by excluding accidents, collisions, and by saving life and health of people in the areas of navigation.

To accomplish the aim, the following tasks have been set:

– to define algebraically and predicatively conditions for transversal (without intersection, collisions, contact) transition trajectories under modes of EAE coincidence of circumstances, requiring that vessels should be maneuvered by means of operational control as the inertial objects in STC;

– to develop technological processes for the algorithmic symbol denotation of the initial and resulting (intermediate) state of the vessel's position in the interval of realization of a safe local maneuver;

– to substantiate the effectiveness of safe local maneuvering processes aimed at preventing all the identified collisions without entering dangerous navigation regions in a route space.

4. Materials and research methods

Methodological essence of algebraically-symbolic formalization aims to achieve real effective safety for a sailing vessel and human lives aboard it. This is performed through preliminary monitoring of STC with coordinates x, y, t of the predicted Δx та Δy zones of route $P(x+\Delta x, y+\Delta y, t_i+\Delta t)$ relative to the current position $P(x_i, y_i, t_i)$ of a moving vessel's position. In this case, we take into consideration that in case the vessel happens to be under conditions of active influence exerted by factors of non-stationary EAE, there are increasing risks to approach the emergency (pre-crash) state.

The reasons for this (HRA) are the complexity [26–29], which is caused by the following key properties of modern practical navigation tasks:

$$SNA_{K-1} \Rightarrow SNA_K \Rightarrow SNA_{K+1};$$

– time complexity of embedded subintervals in T_o $\tau_j \in t_j \in T_j, \quad \forall j=\overline{I,L}.J \in N$ life cycles of many rate-different parallel processes that depend on rate-different temporal preceding and current states of the participants in a dynamic situation;

– spatial three-dimensional complexity $x_i, y_i, z_i, \ \forall j=\overline{I,K}$ of configurational STC with the arrangement of a large number of various factors of influence and movable 3D objects on the resulting dynamic events in a multidimensional space;

– algorithmic complexity (informational- computational number of computer operations) $C_k(t,X), \quad \forall k=\overline{I,N}$ as a consequence of unformalized heuristic concepts and situational models with linguistic variables and at different situational reasons with undefined parameters;

– integrated complexity of combining

$$I=\sum_{l=1}^{M} I_l(C_{kl}), \quad \forall j=\overline{I,M}$$

objects with a large number of hierarchical levels of interaction on horizontal and vertical layers, including intra-layer structural-functional interdependences [5, 30–32].

The lack of a unified formal model of CDS efficiency predetermined the application of a classical approach implying the decomposition of the complex pattern into simpler parts (components, elements). We shall decompose each CDS into simplified subsystems (meta-, macro-, micro-components), which are interconnected.

The time complexity will be decomposed into life cycles, classes of situations, modes of operation, phase transition processes, pulse disturbances. The nested intervals of rate-different processes will be integrated in uniform complex dynamics with an universal time axis and a unified reference.

The spatial complexity will be decomposed into problems on determining a sphere of influence, service areas, sectors of influence specificity, local areas of interaction with respect to the actual geometrical parameters of shapes and distances [10].

The algorithmic STC and CDS complexity will be decomposed into separate typical logic circuits of algorithms. We shall register data exchanges between them in accordance with the specified conditions for transitions to other nodal logical circuits of algorithms. This is executed within the overall graph of the integrated algorithm for solving a complicated task [1, 3–5].

With respect to the above, we prepared variants for a timeline diagram of events for a pair of vessels whose trajectories, as predicted, at a point of the smallest convergence T_A are safe and have a dangerous shared point of intersection (collision) (Fig. 3).

Our explanation:

space denotations:

ΔX_{min} is the smallest distance of approaching to start the implementation of GAC over a vessel under specified law of maneuvering $U(t, X, W)$;

$\lim \Delta X(t)$ is the natural law of uncontrolled motion due to inertia;

ΔX_{inf} is the smallest permissible approaching distance;

ΔX_{max} is the safe distance farther away from a collision;

ΔX_{sup} is the safe distance with respect to threatening factors of external influence (wind, waves, ...).

stepwise i time intervals that characterize a safe target variant with evasion from collision (Fig. 3, *b*):

T_{Sm} is the time when a change in the mode of operation of the engine and steering machine must be completed;

T_{fm} is the time when as a result of change in the mode of operation of the engine and steering machine the vessel has completed a maneuver leaving behind a situation of dangerous approaching;

T_g is the time when a vessel, upon completing a maneuver, is at a safe distance with respect to the threatening factors of external influence (the target point – goal);

T_A is the time when a vessel has fully completed the maneuver and returned to the scheduled route;

$T_{Sm} - t_0 = \sum_{i=1}^{l} \Delta\tau_i$ – starting from point t_o of the start for activating the task the duration of sequential steps that due to reasons ΔX_{min} were needed to implement:

(i=1) – preliminary prediction of future events to moment T_A;

(i=2) – analysis of the situation and proposed variants to prevent collisions by maneuvering;

(i=3) – decision-making and choice of maneuvering path;

(i=4) – processes to moment T_{Sm}, which characterize that changes in the modes of operation of main engine and steering machine have been completed;

$T_{fm} - T_{Sm} = \sum_{j=1}^{m} \Delta\tau_j$ – duration of successive m steps, needed, for reasons of trend $\downarrow\Delta X_{inf} < \Delta X_{min}$, for implementing the processes of active maneuvering and adaptive control over the laws of changing the course and speed of the vessel, as consequence of which the preceding trend was changed to the opposite trend $\uparrow\Delta X_{max}$y at moment T_{fm} when a stage of avoidance of collision is completed [5, 10];

$T_g - T_{fm} = \sum_{k=1}^{n} \Delta\tau_k$ – starting from moment T_{fm} to the target moment T_g (goal, $\uparrow\Delta X_{sup}$), n steps are executed to return the vessel to the implementation of the planned route, and to continue control over a given pair of vessels.

In the case when new dangerous factors emerge, time countdown begins anew from moment t_o with situational algorithms executed in order to ensure permanent position within SNR according to the planned route and to prevent a collision [12].

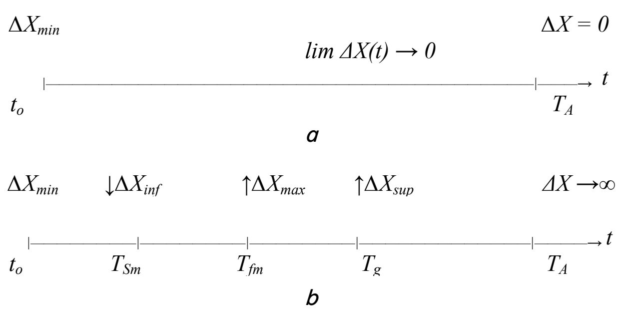

Fig. 3. Timeline of prediction of the course of events for a pair of approaching vessels: a – variant excluding the implementation of maneuver of avoidance, the result of which is the collision at moment T_A (ΔX=0 is the distance between the sides of both ships) [15]; b – timely implementation of maneuver of avoidance and prevention of the collision

5. Results of research into maneuvering movements

5. 1. Algorithmic transformations in the intelligent systems of navigation and control over vessel motion

Each algorithm, formalized by the criteria of STC and CDS [5, 23, 24], is performed by the following steps.

Step 1. Mathematical model of the empirical object of research (a phenomenon or a process) is the totality of accumulated and documented knowledge, facts, arguments, axioms (assumptions). Partial models make it possible to build a coherent, logical, perfect, and noncontroversial structure that reflects basic, key properties of the CDS object.

In the framework of the targeted measuring experiment, objects and mathematical models are not fully identical. A mathematical model replaces a complex natural object only. The simplified mathematical model works (under constraints of modeling tools) independently of the actual object. This enables the speed of obtaining measurement results during modeling. Therefore, the key process is control over errors at each stage of CDS modeling. Special attention to infallibility is needed at the defined given set X, which consists of basic elements $x_i \in X$, $\forall i = \overline{1,n}$ – structural parts of a non-empty totality. Based on the choice and grouping of elements of set X, homogeneous in properties, it is possible to compose different classes of C objects (points) as a respective $\Im$ subset. The open set of space C consists of the elements of a given totality and the empty set. Certain combination of the assigned open sets is called the topology of space C, or a topological structure. Based on topology $\Im$, a system of vicinities is built. In this case, vicinity U is the vicinity of point $x_i \in X$ that determines $U(x_i) \in \Im$ if $x_i \in U$.

Step 2. A pair of $(X, \Im)$ sets is called a topological space if the following conditions are met:

$$(\forall x_i \in X)(\exists U \in \Im): x \in U, \quad (1)$$

$$(\forall x \in X)(\forall U(x), V(x) \in \Im)(\exists W(x) \in \Im): Wx \subseteq U(x) | V(x). \quad (2)$$

Then two different points of space are separated (scattered) in topology $\Im$ via vicinities. It is obtained as a result of the fact that every pair of points in Hausdorff space $(X, \Im)$ has vicinities that do not intersect.

Step 3. Topological space $(X, \Im)$ will prove to be a Hausdorff space when, in addition to conditions (1) and (2), denotations (2) will be complemented with the additional condition

$$(\forall x, y \in X, x \neq y)(\exists U(x), U(y) \in \Im): Ux \cap \cup U(y) = \varnothing. \quad (3)$$

Step 4. Subfamily $(B \subset \Im)$ of open sets is called the basis of topology $\Im$ if each element from $\Im$ can be represented in the form of association with B.

Step 5. Metric space for class C objects (points (x, y, z, ...) sets rules for each pair of points $x, y \in C$ of STC if the defined real number $d(x, y)$ (as a metric of distance between x and y) is such that

$$d(x, y) = 0, \quad \forall x \in y,$$

$$d(x, y) \leq d(x, y) + d(y, z). \quad (4)$$

Thus, for all elements x and y out of C, the triangle inequality holds, as well as the properties of measure

$$d(x, y) \geq 0, \, d(x, y) = d(y, x)$$

and symmetry.

The above-mentioned measures enable the representation (transformation, correspondence, operation, function $x \to x' = f(x)$ when constructing a mathematical model in the region of images relative to the actual natural (physical) objects in the region of the original. Measure (3) and (4) can be used for physical quantities: length, area, volume, mass, force, pressure, distance, etc. These are the examples of positive value. Negative values must be taken into consideration along the scale with a marked zero position. These opposite physical magnitudes can be formalized. For example, electric charge $\pm q$ can be characterized by the movement of atoms and electrons around own core with a charge.

Step 6. Real function *q*, assigned in space *X* on σ algebra of subsets of the measurable space using a $q(A)\in\Re$ set of real numbers along a straight line is called the charge if the following conditions are applied:

$$q(\varnothing)=\varnothing,$$

$$q\left(\sum_{j=1}^{\infty}A_j\right)=\sum_{j=1}^{\infty}q\left(A_j\right),$$

$$a=(A,\,\Omega_F,\Omega_p),$$

where *a* is the algebraic object for which *A* is the carrier of algebraic system of a non-zero set of elements with sets of Ω_F functions (operations over *A*) and predicates (logical relationvessels over *A*). The function of charge $\pm q$ is countable and adaptive; in this case, non-negative and negative subspaces do not intersect.

Step 7. A measurable topological space with charge *q* denotes a threesome $(X,\,\Im,\,q)$ for error-less determining (description and modeling) [3, 5].

Mathematical problem on measurement to represent actual processes of the vessel motion involving the systems of navigation and motion control within each HRA has two components.

The first component formulates and describes known relation vessel (interdependence) between all mathematical models for the objects of a measurement process. In this case, we include the following partial tasks: values of parameters, structure, initial and boundary conditions for the existing regions and specific constraints for expenditures, resources, mechanisms.

The second component implies the formation of typical trivial subtasks that need to be solved in steps. In this case, we define the cycle set by proving a potential error and guaranteed estimate of result quality. For most applied problems, solution that satisfies requirements and stated (initiated, actualized) tasks is contained in the implicit form in the statement of a given problem [2, 3, 6–8, 14, 21, 25]. Therefore, to prevent structural computational quality of the algorithm, one must additionally perform the necessary transformations into explicit form.

5. 2. Control over safe condition of the vessel moving in a heterogeneous wave environment

While a vessel sails the sea in stormy weather, its hull is exposed to various negative dynamic factors of wave influence. These include: resonance in pitching, position of the vessel on two edges of waves, turbulence zone, impacts from particularly large waves, as well as shoving waves that emerge during exposure to multiple wave systems (wind, swell, different directions of waves [3, 4, 9, 11, 19, 21, 25].

In a general case, heterogeneity of environment cannot be changed. It is necessary to create an adaptive system at the object itself, which would, during motion, respond to continuous changes in the environment.

While navigating along the planned trajectory, it is necessary to know in advance about the expected irregularities. We shall synthesize control system for the criterion of vessel's sensitivity to obstacles to its movement in a heterogeneous environment.

Heterogeneity of the environment is represented as a space-time random field. That is why the first stage is to obtain in real time information about the spatial distribution of irregularities for any point in time, that is, the sequence of realization of the frozen field.

$$Q(t)=Q(\rho,t);\rho=\{x,y,z\}. \qquad (5)$$

If the field slightly changed its structure by the end of control time, that is remained almost frozen, then we can disregard temporary changes in the field, and operate only by spatial characteristics. The degree of frozen field can be estimated by the magnitude of ratio of the mean square of field's values at moments *t and t*+T_p to the variance of the field

$$\frac{\left[Q(\rho,t)-Q(\rho,t+T_\eta)\right]^2}{Q^2(\rho,t)}=$$
$$=\frac{Q^2(\rho,t)-2Q(\rho,t)Q(\rho,t+T_\eta)+Q^2(\rho,t+T_\eta)}{Q^2(\rho,t)}=$$
$$=2\left[1-R(T_p)\right]. \qquad (6)$$

Correlation functions of such geophysical fields as sea waves are appropriately approximated by exponential dependence.

$$R(\tau)=\exp\left(-\alpha\frac{\tau}{\Delta T_k}\right);\;\; R(T_p)=\exp\left(-\alpha\frac{T_p}{\Delta T_k}\right), \qquad (7)$$

where *R* (τ) is the time correlation function of the field of environment irregularities, ΔT_k is the interval of correlation time.

Conditions for a dependence can be written in the form

$$Tp/\Delta T_k\ll 1. \qquad (8)$$

In this case, the larger the vessel, the bigger an increase in the constant of control time T_p. Then condition (8) may not be fulfilled for massive vessels. That is why at the second stage of enabling the adaptation of objects to environmental perturbations we must have time dimensions – evaluation of random field of sea waves. The prediction is made easier by the fact that time μ and spatial *K* frequencies of the same spectral components of sea waves are related via a dispersion relation

$$\mu^2=gK, \qquad (9)$$

where g is the acceleration of gravity.

If we managed to obtain for certain time *t* a two-dimensional spatial implementation of upheavals in wave relief *z*(*x, y, t*)*,* then we shall perform a two-dimensional Fourier transform for the obtained implementation of a wave relief in the form of the sum of all flat spectral components

$$z(x,y,t)=$$
$$=\sum_i\sum_j a_{ij}*\cos\left[K_i(\cos Q_j+y\sin Q_j)-\mu_i t-\varepsilon_{ij}\right], \qquad (10)$$

where Q_j is the direction of spectral component along the *x* axis; a_{ij} is the amplitude of elementary wave plane.

This amplitude can be expressed through a spectrum of amplitudes of the complex spectrum, or the energy spectrum

$$a_{ij} = \sqrt{2S_Z}\,(K_i;Q_j)\Delta KHQ.$$

It follows from the dispersion relations that each spectral component of a long wave $\Lambda_i=2\pi/\mu_j$ has a corresponding propagation rate

$$C_i = \frac{\Lambda_i}{T_i} = \frac{2\pi}{K_i} \Big/ \frac{2\rho}{\mu_j} = \frac{\mu_j}{K_i} = \sqrt{\frac{g}{K_i}}. \quad (11)$$

We shall change in time the components of phase $\phi_i = \mu_i t$. This can be expressed through a wavenumber

$$K_i\phi_i = (gK_i)(gK_i)^{\frac{1}{2}} t$$

as a spatial characteristic.

To predict increases in the wave relief elevation at time $t+\Delta t$, each spectral component must be assigned with an additional phase shift

$$\Delta\phi_i = (gK_i)^{\frac{1}{2}}\Delta t.$$

We obtain a relief spectrum for time $t+\Delta t$:

$$z(x,y,t+\Delta t) =$$
$$= \sum_i \sum_j a_{ij} * \cos\left[K_i(\cos Q_j + y\sin Q_j) - (gK_i)^{\frac{1}{2}}(t+\Delta t) - \varepsilon_{ij}\right]. \quad (12)$$

We shall perform an inverse Fourier transform, the result of which is the desired relief of waves $z(x,y,t+\Delta t)$.

The sequence of operations for obtaining a predicted relief can be schematically written in the form of the following sequence:

$$z(\rho t) \to F\{z(\rho t)\} \to s\downarrow(Z)\uparrow(iK,Q,t) \to$$
$$\to s\downarrow(Z)\uparrow(iK,Q,t+\Delta t) \to$$
$$\to F^{-1}\{S_z(iK,Q,t)\} \to z(\rho t+\Delta t). \quad (13)$$

Thus, if one performs operations (12) and (13), then it becomes possible, in time Δt, to predict the value of elevation of waves relief in any point ρ (x, y).

It is obvious that proper control requires a sequence of implementation

$$z\left[\rho, t+\Delta t(0<\Delta t<T_\eta\right].$$

Prediction of total relief of waves in the vicinities of the vessel's trajectory makes it possible to predict the emergence of particularly large waves. It is not possible to take preemptive measures without forecasting emergency situations.

5. 3. Estimation of effectiveness of the stages of operational planning when vessels navigate in high risk areas

Construction of functionally stable CDS [5, 10, 31] requires a calculation technique. It should objectively assess the degree of efficiency and coefficient of stability of a clearly defined structural-functional subsystem of GAC with means of control over a vessel motion. Navigation support to movable vessels for determining the location in the coordinate-time space of controlled states is based on key concepts [1] in the form of the following four sets.

1. Operational plan (OP) for maneuvering, avoiding collisions, dynamical changes in HRA includes a series of substantiated stages or appropriate successive steps

$$P = \{p_1, p_2, \ldots p_i, \ldots p_l\},$$

where each step p_i, $\forall_i = \overline{1,l}$ of plan ℓ is the total number of steps in a specific plan for dynamic maneuvering.

Terminal values of state parameters (spatial, temporal, physical, technological, technical, etc.) are compiled in the determined T time interval or a fragment of OP for the future projected period of vessel operation in a specified motion zone [5, 25, 31].

2. Activities of dynamic functions that need to be performed in order to implement a particular step, as a transition from the preceding state of OP to the following, over time interval $\Delta\tau<<T$ of transition process of dynamic positioning, in general make up the following set of standard operations

$$D = \{d_1, d_2, \ldots d_i, \ldots d_m\},$$

where m is the total number of operations d_i, $\forall_i = \overline{1,m}$ of the law of control over working bodies of the vessel within a particular stage ΔT_j for obtaining the final terminal effect.

3. Resource capacity of IAS implementers and guaranteed logistical support, capable of performing necessary operational activities via synergistic interaction between the following IAS

$$R = \{r_1, r_2, \ldots r_i, \ldots r_n\},$$

where n is the number of specific IAS with appropriate sources of specific own resources, which together are capable of ensuring quality of the joint operational activity in a predefined time interval T of a given service area.

4. Effects of the optimal maneuvering of a vessel in a given HRA are determined in comparison with the variant of a non-adaptive navigation support based on obsolete technologies. Substantial reduction of risk of collision by preventing critical events in CDS makes it possible to obtain the following set of effectiveness estimates:

$$E = \{e_1, e_2, \ldots e_i, \ldots e_k\},$$

where k is the number of positive effects, which are additional through multivariate synergistic real-time control and minimization of IASs resources spent for each step or a stage of the plan not implemented as yet [22, 25, 31].

Procedure for estimating the effectiveness of any OP, which implies the algebraization of relations between these sets for the purpose of navigation support to vessels, is proposed to perform by the following stages.

1) Relations of reliability and quality of the relationship of fuzzy sets between the stages of OP and respective activities D are determined by L. Zadeh method [28, 29, 32] in the form:

$$F: P \times D \to [0,1], \quad (14)$$

where [0,1] is the universal interval for estimating in relative units the degree of dependence between elements of $(P\times D)$ sets.

2) Similarly, the function of relationship between linguistic variables D and R will be defined by the following analytical form:

$$\phi : D \times R \to [0,1], \quad (15)$$

where $\varphi(d_j, r_s)$, $\forall d_i \in D$, $r_s \in R$ is the measure of belonging or the degree of compatibility between resource capacity of a specific information automated system and operational activities when an on-board multi-functional complex executes a transition process of OP with changes in functional states, to determine numerical values for estimates.

3) Formalized analytically, and assigned informational-sign relations (14) and (15) are correlated in the form:

$$\Omega : P \times R \to [0,1], \quad (16)$$

where [0,1] is the universal scale, which characterizes the relative membership function with values of estimates $\mu(p,r)$, $\forall p_i \in P, r_s \in R$, which are calculated for each pair of p_i and r_s.

4) It is appropriate to qualify the obtained set of estimates by splitting into two separate classes. The boundary between these two classes is determined by condition:

$$k \le M_e\left(\sum_{S=1}^{n}(r_s)\right) + \frac{\sum_{S=1}^{n} r_s - M_e\left(\sum_{S=1}^{n} r_s\right)}{\sum_{S=1}^{n} r_s}. \quad (17)$$

A given expression makes it possible for a vessel's automated complex to determine the most important components of OP. Inequality (17) ensures functional stability by combining the most effective sources of various information automated systems.

The presence of so-called "bottlenecks" can be revised in certain parts of OP by excluding and using other, more attractive actors, for more effective criteria of efficiency [7]. Natural and social environmental factors also influence technical means, which enable communication connection. There are many such connections, which is why they significantly affect the quality of routes for data transmission through networks.

Adaptive response to situations with de facto temporary deterioration of partial functions of certain elements necessitates realization of reference for a given automated system that was exposed to a particular impact.

The functional stability of a vessel in a specific forecast time interval of OP implementation is enabled by connecting to additional information automated systems. The co-actors are required to achieve the next targeted step. Effective decision-making is based on the knowledge of estimations of distances as the distances between separate current values and the chosen reference [1].

Each potential informational automated system that is effective within OP must have a positive estimated assessment for the degree of stability of own functional activities. In the case of a negative evaluation, the existing situation of heightened sensitivity to the peculiarities leads to the loss of functionality of a particular software-hardware complex [1, 3, 5, 12, 22].

The degree of stability characterizes design calculation of the functional stability of a particular stage in comparison to the steps in the implementation of OP. During operation, especially under conditions of maneuvering, certain fragments of this stage can be corrected by determining new conditions for motion.

The proposed approach makes it possible to integrate the procedures of adaptation, training, and allocation of functions between a human and a movable object, which moves fast while maneuvering.

The required technical means of the software-hardware complex are implemented by automating the proposed technological processes. Systems for making key decisions in the space of possible threatening situations in CDS under automated mode accurately assess conditions for control in real time.

5. 4. Typical plan of structural analysis under operational conditions

We shall consider a typical example of structural analysis under operational conditions [25]. In the water area where a programming task is implemented relative to the planned voyage during motion of a vessel in line with the system of distribution of motion, introduced by the IMO Resolution IMO A.572 (14) dated November 20, 1985 [17, 18, 23], the maneuver is resolved. The systems of distribution of vessels motion, established by the International Maritime Organization for areas with intensive navigation, necessarily require that quality of motion safety control should be improved. The dynamics of returning to functional state is implemented by means of control over vessel motion. We shall model the vessel as a moving object according to the third order differential equation

$$P^3 x + c_2 P^2 x - c_1 P x = c_z f(t), \quad (18)$$

where $c_2 = a_2/a_3$; $c_1 = a_1/a_3$; $c_z = h/a_3$; a_3=const are known coefficients at corresponding variable parameters of the differential equation; $P = d/dt$ is the operator of differentiation; in this case, first order; $f(t)$ is the external disturbance, reflecting in the examined interval $0 \le t \le T$ a respective time function of change in the influence of a given factor of the external environment (for example, resistance forces to current, wave field, aerodynamic head, etc.).

In accordance with the aforementioned rules for constructing a structural matrix for a specific model according to equation (18), we obtain the following (Fig. 4) structural matrix, where $1/P$ is the integration operator. In this case, there are two "defective" (failing to ensure resistance) contours.

The contour for the first derivative Px closes via positive $C_1>0$ coefficient. The second contour is open for zero derivative from variable x, that is non-closed. Thus, the object in a given case has resistance neither for the main coordinate x, no for speed Px of its change.

Restoration of the fundamental property of the object to retain the stability of operation under conditions of the explicit influence of external environmental factors $f(t)$ is achieved by adding to the object an appropriate regulator to implement joint compatible functions according to the following equations

$$P^3 x + C_2 P^2 x - C_1 P x = C_\Sigma f(t) - b \cdot U(t),$$

$$U(t) = K_1 P x + R_0 x, \quad (19)$$

where b is a coefficient of interface interaction between the object and regulator;

P^3x	P^2x	Px	x		f
$1/P$	$-C_2$	C_1			C
1	$1/P$				
	1	$1/P$			
		1	1		

Fig. 4. Core of structural matrix of the examined object with two elements of instability according to the third order differential model (18)

U	CBO	P^3x	P^2x	Px	x		K_{33}	f
Σ				K_1	K_0		-1	
1	b							
	1	$1/P$	$-C_2$	C_1				C
		1	$1/P$					
			1	$1/P$				
				1	1			
				1	1		Σ	

Fig. 5. Structural matrix (19), extended for core (18) via a decision-making unit with means of automated control, force controlling element (FCE) of the vessel, and a feedback channel, which closes the circuit to guarantee stability

$U(t)$ is the control law, according to which a coordinate at the output of regulator corresponds to the value of signal at the input of the force controlling element, which provides for the counteraction (with the opposite sign but sufficient capacity) to factor $C_\Sigma f(t)$ of the external environment. Structural matrix of model (19) is shown in Fig. 5 representing the new components that ensure the restoration of stability under action $f(t)$ of operational disturbances.

Thus, the stability of implementation of the operational motion of the vessel is provided by the means of automated control, which satisfy the required conditions for structural stability according to equations (19) to compensate for the impact of $f(t)$ disturbance [25]. In this case, sufficient parametric conditions for analytical construction of the required regulator are provided by inequality:

$$C_2(bk_1 - c_1) > bk_0. \qquad (20)$$

In all cases of multidimensional CDS, the above principles of structural-parametric transformations ensure stability of the operating modes. However, if necessary, a more detailed study of the quality of trajectory control should be implemented through this procedure. The number of transformations depends on each diagonal matrix affected by the specific components of n-dimensional disturbance.

6. Discussion of results of applying a method for the algebraic-symbolic determining of operational conditions for safe motion of a vessel in a non-stationary environment

The obtained results of modeling of several situational maneuvering modes confirm the efficiency of finding symbolic conditions for the existence of transversal (safe) trajectories for maneuvering movements of the vessel. This allows the failure-free execution of transportation work for technical, technological, economic, environmental, and social performance indicators. Situational manifestations of adverse navigation conditions under non-stationary risky conditions are unambiguously defined.

However, the modes of dynamic coincidence of many threats at the same time are not considered. At present, emergency or global threats, when they suddenly approach the vessel's hull, do not allow timely safe response.

The systems of distribution of the traffic of vessels, established by the International Maritime Organization in areas of intensive navigation, necessarily require improvement of the quality of traffic control safety.

The proposed algebraic-symbol method makes it possible to eliminate the existing situational uncertainty in the dynamic development of threatening effects of EAE factors during unwanted coincidence of uncontrolled circumstances. This makes it possible to find local areas for safe navigation. Thus, it warrants safety of people's lives and storage of cargoes aboard the vessel. The proposed methods could be implemented in information-control systems on water transport and in navigation systems, traffic control systems, for sea and river vessels of different purposes.

Promising directions of improvement, which has not been covered in present paper, could be implemented using means of information technology by extending the number of constituent elements of the specified sets in an algebraic system.

The results of present research are promising for the implementation into modern systems that operate automated vessels, as well as systems for training operators-navigators.

7. Conclusions

1. We have devised a method for the formalized predicative determining of zones of safe and dangerous navigation areas directly during voyage. A given method defines the compensation of threats in the form of a dynamic current influence of factors from the non-stationary external environment that covers the planned route of a vessel.

2. We have defined in the form of algebraic-symbol rules conditions for guaranteeing life safety along the vessel's controlled trajectory from the beginning of the maneuver to its completion along the rest of the planned route in a specified space-time continuum. The safety and effectiveness of a trajectory are predicted based on resources that are necessary and sufficient for the criteria <<computational stability – continuity>>. The logic of these conditions allows a permanent continuous operational control aimed at the prevention of accidents and disasters that might be approaching dynamically.

3. The techniques are proposed for the dynamic real-time regulation of technical and technological solutions for the safe motion of a vessel along the transversal trajectories. The algorithms guarantee entry into secure navigation areas only. Computational efficiency of computer implementation makes it possible to apply additional modules for the algebraization of rules and decisions for a wide range of types of vessels by purpose, area of navigation and tonnage. There are no constraints on taking into account significantly remote features calculated in heterogeneous, non-stationary and distributed underwater, water and surface waters.

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